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Short Paper

U-series dating of Locality 15 at Zhoukoudian, China, and implications for hominid evolution

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Abstract

This paper reports U-series dates on speleothem samples from Locality 15 at Zhoukoudian, one of the richest Paleolithic sites in northern China. The age of the lower part of Layer 2 is securely bracketed between 155,000 and 284,000 yr. The underlying Layer 3 dates back at least 284,000 yr. Layer 4, further below, should be older still, possibly by a cycle on the SPECMAP time scale before 284,000 yr ago. These ages, much greater than the previous estimates of 110,000–140,000 yr from U-series and electron spin resonance dating of fossil teeth, suggest that Locality 15 was broadly contemporaneous with Locality 4 (New Cave) and with the uppermost strata of Locality 1 (Peking Man site). The physical evolution and cultural development evidenced by the timing of the Zhoukoudian localities are in line with the opinion of Chinese anthropologists for a regional transition from *Homo erectus* to archaic *Homo sapiens*.
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Keywords: Locality 15; Zhoukoudian; U-series dating; Speleothem; Paleolithic; Human evolution

Introduction

Zhoukoudian, a small town ~50 km southwest of the city of Beijing, China, is world-renowned for the discovery of Peking Man. Zhoukoudian Locality 15 is a particularly rich Paleolithic site located on the southern slope of Longgushan (Dragon Bone Hill), about 70 m south of Locality 1, where Peking Man was discovered. The artifact- and fossil-bearing deposits in a collapsed cave were discovered in 1932 by a field team led by W.C. Pei during an exploration to define the boundaries of Locality 1 (Pei, 1939a). Excavations were undertaken between 1935 and 1937, yielding more than 10,000 stone artifacts, a large number of fossils representing at least 33 mammalian species together with abundant proof of the use of fire.

Around the area of Zhoukoudian, a total of 27 localities have been identified. Among them, Locality 15 is the second richest occurrence of archaeological finds, next to Locality 1. Fieldwork at the site was interrupted by World War II, and only two preliminary reports were published in the 1930s (Jia, 1936; Pei, 1939a). Since then, its valuable collections have not been studied in detail. No more than a few years ago, one of us (XG) reinitiated archaeological and chronological studies of the site (Gao, 2000a).

For about 20 years, there has been an intense debate over the origin of modern humans between the exponents of two competing hypotheses, multiregional evolution (e.g., Wolpoff et al., 1984, 2001) and “recently out of Africa” (e.g., Stringer and Andrews, 1988; White et al., 2003). Whether *Homo erectus* at Zhoukoudian was a direct ancestor of later eastern Asian populations or a side branch in human evolution impacts directly on the hotly debated issues (e.g., Rightmire, 1998). Reliable dating of the localities at

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Zhoukoudian and understanding of their temporal relations are key to resolving the phylogenetic status of Asian *H. erectus*. This is all the more important considering the fact that these localities have been generally taken as reference cross sections for disciplines of the middle–late Pleistocene geology in northern China.

On the basis of archaeological and biostratigraphic evidence, various hypotheses concerning the chronology of Locality 15 have been proposed. Jia (1936) considered at first that there was no major difference between this site and Locality 1. But later, he suggested that Locality 15 was contemporaneous only with the upper horizons of Locality 1 (Jia and Huang, 1990). On the basis mainly of lithological similarity of Layers 2–3 at Localities 1 and 15, Jia and Huang (1990) proposed that Localities 1, 4, and 15 were originally contiguous within a giant cave system. While complying with the suggestion that Localities 15 and 1 were deposited within the same geological stage, Pei (1939a) emphasized that the former was distinctly younger than the latter. The difference centers upon whether there is an overlapping time period or rather a substantial gap between the two localities. Contrasted with the relatively unimportant difference on its relative position, the geological age of the site has been variably placed into early, middle, and late Pleistocene (e.g., Pei, 1939b, 1948; Qiu, 1985). Such a disparity reflects limited resolution of the relative dating based upon biostratigraphic correlations, especially in early half of the last century. Such ambiguities can only be resolved using well-established radiometric dating techniques.

In the late 1970s, a multidisciplinary study on Locality 1 was organized. Numerical dating was carried out using several dating techniques. The following age sequence was proposed for strata at Locality 1: ca. 230,000 yr for the uppermost Layers 1–3, based on ^{230}Th/^{234}U dating of fossils; ca. 500,000 yr for the lowest stone artifact-bearing Layer 10, based on fission-track dating of sphene grains extracted from ash deposits; and ca. 700,000 yr for the lowest fossiliferous Layer 13, based mainly on paleomagnetic stratigraphy (Zhao et al., 1985). The newly established time frame for Locality 1 coupled with the recognition of a much younger Locality 15 prompted Qiu (1985) and Zhang (1987) to suggest that the latter should be early late Pleistocene in age. This age assignment, implying a gap of ~100,000 yr between Localities 1 and 15, has been widely accepted by Chinese scientists.

Since then, along with the progresses of Quaternary dating techniques, Locality 1 has remained an important target for chronological studies. Electron spin resonance (ESR, Grün et al., 1997), U-series (Yuan et al., 1991), and fission-track (Guo et al., 1991) dating methods have been applied, yielding results in general agreement with the aforementioned range. By contrast, the only numerical dates for Locality 15 were U-series and ESR determinations on fossil teeth from Layer 2. The age results, in the interval 110,000–140,000 yr ago, appear in basic agreement with the previous estimate of early late Pleistocene (Gao, 2000a).

However, as U-series and ESR dates on fossils depend highly upon the assumption of U-uptake history, which is a priori unconstrainable (Bischoff et al., 2003; Pike et al., 2002; Shen, 1996), the accuracy of the results for Locality 15 and for the upper strata of Locality 1 remains equivocal. On the other hand, the validity of the U-series dating of carefully selected, pure, compact, and well-crystallized cave calcites has been well demonstrated (Ludwig et al., 1992; Schwarcz, 1992). With high-precision thermal ionization mass spectrometric (TIMS) U-series dating of speleothem calcites, Shen et al. (2001) reinvestigated the chronology of Locality 1. Results show that No. 5 Skull from Layer 3, the youngest member of the Peking Man family, dates back at least 400,000 yr, and is much older than the previous estimate of 230,000 yr.

When carrying out field investigations at Locality 1, we also paid attention to nearby Locality 15 for existence of datable calcite specimens. On the presently exposed surface of the limestone breccia, a secondary calcite sample (ZSW-1) was collected. Preliminary ^{230}Th/^{234}U dating of this sample by α spectrometry (AS) gave an age of 240,000 ± 50,000 yr, which was confirmed by a TIMS determination at 230,000 ± 2000 yr. This points to the possibility that, just like Locality 1, Locality 15 may also be much older than previously estimated. Subsequent fieldwork at Locality 15 enabled collection of a total of ten well-located speleothem specimens. In this paper, we present U-series results of these samples and discuss their implications for human physical and cultural evolution.

Samples in stratigraphic position

On the basis of former descriptions (Jia, 1936; Pei, 1939a) and by excavating a test square, Gao (2000a) restudied the depositional sequence and subdivided it into the following layers, which are shown in Figure 1 (numbers from top to bottom).

Layer 1: lime–kiln waste, gray–white and gray–black, slightly consolidated, ~4-m thick.
Layer 2: sandy clay, yellowish, slightly cemented, with small angular limestone blocks, rich in artifacts and fossils, ~1.75-m thick.
Layer 3: sand and clay supported limestone breccia, gray–black, strongly consolidated, average thickness 1.25 m.
Layer 4: sandy clay, reddish, without cementation, with occasional angular limestone, rich in fossils, an exposed section of ~75-cm thick, total thickness unknown.

When speleothem calcites are used as time markers, only pure, compact, and well-crystallized specimens with well-defined stratigraphic context may ensure reliable and

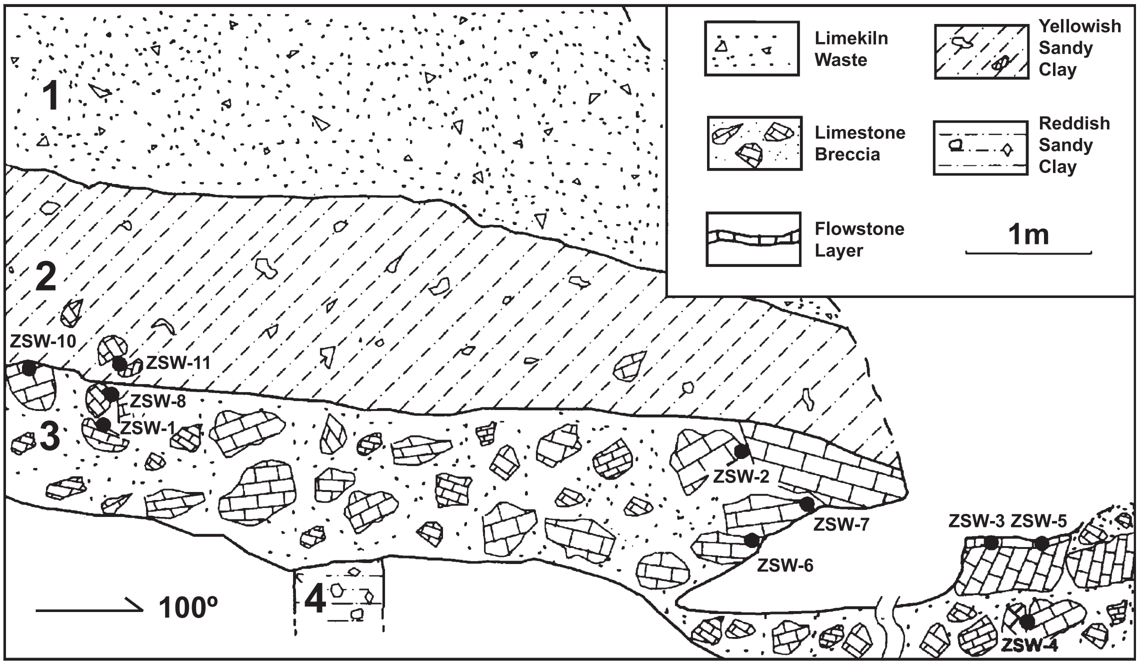

Figure 1. Sketch profile showing locations of the dated samples from Locality 15, Zhoukoudian.

meaningful dates. Along the depositional sequence of Locality 15, only one suitable sample was taken from Layer 2 and all others from Layer 3. Their positions on the main profile are shown in Figure 1.

A thin sheet of flowstone about 2–4-cm thick overlies a big limestone block more than 1 m across near the surface of Layer 3. With clear laminae and natural form, this flowstone should be formed in situ and in its primary position, indicating that at the time of its formation at least part of the roof survived. This flowstone is mostly composed of reddish clay-rich calcites. However, a sublayer ~2-mm thick in the middle appears to be quite pure and compact. Samples ZSW-3 and -5 were collected from different portions of this sublayer.

In small cavities between limestone blocks of Layers 2 and 3, flowstones or calcite veins with clear laminae and limited extension may be found, which should be deposited from percolating ground water. ZSW-11 was taken from such a formation in the lower part of Layer 2, about 10 cm above the Layers 2–3 boundary. From similar formations of Layer 3, four more samples were taken, ZSW-8 being few centimeters below the Layers 2–3 boundary, and ZSW-2, -4, and -7 at different locations.

Patches of translucent calcite crystal aggregates occur on limestone blocks of Layer 3. Because no depositional laminae were recognizable, the calcite crystals are interpreted to have precipitated in fissures between limestone fragments from very slowly seeping groundwater. ZSW-10 was taken from such a formation on a limestone block about 40 cm across at the boundary of Layers 2–3. Another formation some 40 cm lower was collected as ZSW-1. ZSW-6 was taken from a similar formation at the middle part of Layer 3, which grows on the ceiling of a cave-like cavity hollowed out by natural processes.

Results and interpretation

For samples with sufficient quantity, conventional AS was applied to measure $^{230}Th/^{234}U$ and $^{234}U/^{238}U$ ratios. For those too small for the classical method or in need of a better precision, TIMS dating (Edwards et al., 1986/87) was carried out by JXZ. The U–Th isotopic ratios and derived age results using AS and TIMS are presented in Tables 1 and 2, respectively. The agreement between the results from the two techniques confirms the reliability of the dates and highlights the importance of TIMS method for more precise dating.

In fact, the calcite grains analyzed as ZSW-5(I) and (II) are rather pure. However, their low U contents contribute to rather low $^{230}Th/^{232}Th$ activity ratios, resulting in large detrital Th correction and dates of poor precision. To address this problem, great effort was made to pick out the purest possible crystals, and a much improved $^{230}Th/^{232}Th$ ratio of 31.5 was achieved for ZSW-5(III) (Table 2). Three detrital-corrected ages of this sample yield a weighted mean of 284,000 $\pm$ 10,000 yr, marking the minimum age of the underlying Layer 3 and the maximum age of the overlying Layer 2. Sample ZSW-3, though with a low $^{230}Th/^{232}Th$ ratio of only 3.6 due to detrital contamination, yields a result consistent with that of ZSW-5.

Apart from ZSW-3 and -5, all other samples are secondary calcite formations. This kind of material is conventionally interpreted to represent the minimum age

Table 1
Alpha spectrometric U–Th isotopic ratios and age results

Sample	U (ppm)	$^{230}Th/^{232}Th$	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	^{230}Th age (10^3 yr)	^{230}Th age (Corrected, 10^3 yr)
ZSW-1	0.47	139	1.197 ± 0.048	0.930 ± 0.046	240 ± 50	
ZSW-4	0.13	16.6	1.275 ± 0.060	0.552 ± 0.038	84.2 ± 8.5	81.3 ± 8.5
ZSW-6	0.29	82.6	1.157 ± 0.040	0.960 ± 0.048	278 ± 64	
ZSW-7	0.51	72	1.201 ± 0.052	0.710 ± 0.041	128 ± 15	

All isotopic ratios shown are in radioactivity. The ages are calculated using program ISOPLOT/EX of Ludwig (2000). Half-lives of ^{230}Th and ^{234}U are 75,380 and 244,600 yr, respectively. All errors are $\pm 2\sigma$. For samples with $^{230}Th/^{232}Th$ ratio less than 50, corrected ^{230}Th ages are given, assuming the initial $^{230}Th/^{232}Th$ atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$. This is the value for a material at secular equilibrium and with a bulk earth $^{232}Th/^{238}U$ value of 3.8. The errors are arbitrarily assumed to be 50%.

of the horizon where it was precipitated. So the result of ZSW-11 indicates a minimum age of 155,000 yr for the lower part of Layer 2 (Table 2). Nevertheless, it seems reasonable to argue that at the time of its formation, an overlying layer of carbonate-bearing deposits should have accumulated to certain thickness to allow the infiltrating water to be saturated with calcium bicarbonate. So ZSW-11 may also define the minimum age of the overlying deposits immediately above. The absence of depositional hiatus in Layer 2 deposits excludes major erosion and redeposition event, providing support to the above inference.

Thus, the lower part of Layer 2 can be firmly bracketed between 155,000 and 284,000 yr ago. If the limestone breccia of Layer 3 was resultant from the collapse of a major portion of the cave roof, subsequent sedimentation was presumably a rapid open-air event. So the date on ZSW-11 defines possibly the minimum age for entire Layer 2.

For Layer 3 samples, ZSW-2, -4, -7, and -8 yield results between 81,000 and 174,000 yr (Tables 1 and 2), from which no meaningful age constraints can be inferred. The results on ZSW-1, -6, and -10, between 226,000 and 264,000 yr (Table 2), mark minimum age of the limestone breccia, which is in line with the aforementioned constraint provided by ZSW-5.

Inside a cavern, the interlayered deposits of different physical and chemical properties are records of global climate fluctuations. Underlying the primary flowstone layer from which ZSW-5 was taken are Layer 3 composed of limestone breccia, most probably resulting from cryoclastic activities during an ice age, and Layer 4 of reddish soft sandy clay, presumably accumulated during a warm and humid period. In this regard, Layer 4 might be older than ZSW-5 (284,000 yr) by one glacial–interglacial cycle on the SPECMAP time scale (Winograd et al., 1997). This assigns an age of ca. 400,000 yr to the lower strata of this site.

In any case, a great part of the Locality 15 depositional sequence must be substantially older than previous assignment (110,000–140,000 yr) based on U-series and ESR dating of fossil teeth. As mentioned above, the unquantifiable postdepositional U migration greatly hampers the reliability of the U-series dating of fossils. Comparisons show that the U-series dates on fossils are, as a general tendency for cave sites, much younger than those on associated calcites (Shen, 1996; Zhao et al., 2001). The dating of Sima de los Huesos may be cited as a recent example. Based on combined U-series and ESR dating of fossil teeth, this hominid site was attributed to the period 200,000–320,000 yr ago (Bischoff et al., 1997). However, the U-series dates on a newly discovered overlying flowstone layer define much older ages of 400,000–500,000 yr for the site (Bischoff et al., 2003).

Table 2
Thermal ionization mass spectrometric U–Th isotopic ratios and ^{230}Th age results

Sample	U (ppm)	$^{230}Th/^{232}Th$	$^{234}U/^{238}U$	$^{230}Th/^{238}U$	^{230}Th age (10^3 yr)	^{230}Th age (corrected, 10^3 yr)
ZSW-1	0.3386 ± 0.0003	1966	1.1656 ± 0.0023	1.0639 ± 0.0020	230.4 ± 2.2	
ZSW-2	0.1205 ± 0.0001	49.7	1.2628 ± 0.0049	0.7098 ± 0.0068	86.6 ± 1.3	85.6 ± 1.4
ZSW-3	0.0606 ± 0.0001	3.57	1.0914 ± 0.0030	1.0785 ± 0.0122	351 ± 28	327 ± 59
ZSW-4	0.1201 ± 0.0001	35.4	1.2639 ± 0.0027	0.7459 ± 0.0048	93.1 ± 1.0	91.7 ± 1.1
ZSW-5(I)	0.0570 ± 0.0001	8.70	1.0785 ± 0.0025	1.0597 ± 0.0061	347 ± 15	337 ± 21
ZSW-5(II)	0.0460 ± 0.0001	5.47	1.0664 ± 0.0026	1.0338 ± 0.0079	326 ± 16	310 ± 22
ZSW-5(III)	0.1528 ± 0.0001	31.5	1.1109 ± 0.0020	1.0588 ± 0.0044	281 ± 6	278 ± 6
ZSW-6	0.2819 ± 0.0004	1637	1.1718 ± 0.0020	1.1136 ± 0.0042	263.8 ± 4.4	
ZSW-8	0.1346 ± 0.0001	290	1.2048 ± 0.0024	0.8258 ± 0.0035	173.5 ± 1.8	
ZSW-10	0.2951 ± 0.0003	293	1.1703 ± 0.0021	0.9076 ± 0.0042	225.8 ± 3.3	
ZSW-11	0.4252 ± 0.0004	438	1.2121 ± 0.0022	0.9503 ± 0.0058	154.5 ± 2.1	

All items are the same as in Table 1. Roman numerals in the first column denote replicate analyses on different splits of the same specimen. The analyses were carried out at ACQUIRE, University of Queensland, using a procedures described in Zhao et al. (2001).

The present work represents a further step toward the establishment of a reliable chronology for the localities at Zhoukoudian. Layers 1–2 of Locality 1 are now preserved at Locus H with a cross-section of about 2-m thick. Shen et al. (2001) dated three speleothem horizons intercalated in the uppermost 70-cm deposits, obtaining ages of ~144,000, ~300,000, and ~400,000 yr, respectively. Locality 4 (or New Cave) is situated only meters to the west of Locality 15. Three intercalated flowstone layers give U-series dates of ~120,000, ~260,000, and ~300,000 yr, respectively (Shen et al., 2004). These dates, together with the results of this paper, indicate that Localities 4 and 15 and the uppermost strata of Locality 1 are broadly contemporaneous. This is in line with the suggestion that Localities 4 and 15 may represent different chambers of the same cave (Gao, 2000a). On the other hand, as the limestone breccia of Layer 3 at Locality 1 clearly predates its counterpart at Locality 15, the apparent depositional similarity should not be quoted as a supporting evidence for the hypothesized giant cave system proposed by Jia and Huang (1990).

Implications for hominid evolution

As human fossils have not been recovered from Locality 15, the identity of its inhabitants remains unknown. The demonstrated contemporaneity of Localities 4 and 15 suggests that archaic *Homo sapiens*, as represented by a premolar from the former site (Gu, 1978) and dated most likely to >269,000 yr (Shen et al., 2004), should be the toolmaker at the latter. The youngest *H. erectus* at Zhoukoudian as represented by the No. 5 Skull from Layer 3 of Locality 1 is at least 400,000 yr old. The absence of discernible temporal gap between these localities is in line with the opinion of Chinese anthropologists for a regional transition from *H. erectus* to archaic *H. sapiens*, which should take place sometime around 400,000 yr ago.

The line of physical evolution is supported by cultural development. The artifacts of Localities 1 and 15 exhibit many similarities, which would link the two lithic assemblages into the same cultural tradition, i.e., the mainstream small flake-tool technocomplex in North China (Zhang, 1999). Nonetheless, differences between the two assemblages are obvious. Taking the flaking technique as an example, at Locality 1, bipolar flaking was predominant for core reduction, producing 74% of the artifacts from Layer 3 (Pei and Zhang, 1985). In contrast, at Locality 15, it was hammer percussion that became the principal technique, yielding 88% of all the lithic objects (Gao, 2000b). Compared with bipolar flaking, hammer percussion is a more efficient way to exploit vein quartz, an easily available raw material at Zhoukoudian. Besides, more tool types and more refined retouches on tools can be identified at Locality 15 (Gao, 2002). All these show clearly a trend of cultural progress from Locality 1 to Locality 15, which is in support of the evolutionary dynamics of the *H. erectus* populations in China.

The results of this paper warrant further studies of the site. The 1935–1937 excavations were concentrated on Layer 2. Layers 3 and 4 have remained largely unstudied. For Layer 3, it was simply mentioned that on its surface scattered ash heaps associated with flakes, burned bones and plant seeds could be found. For Layer 4, only a section of 75-cm thick was explored, with lots of fossils and a few artifacts being recovered. Given their critical temporal position possibly covering the interface between *H. erectus* and archaic *H. sapiens*, renewed excavations and further multidisciplinary studies, including dating, of the site may hopefully provide important insights into the fundamental issues concerning physical and cultural evolution of middle Pleistocene hominids in North China and in greater East Asia.

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